LOW VOID ADSORPTION SYSTEMS AND USES THEREOF

Field of the Invention

The present invention provides an improved
pressure swing adsorption system, and, more
particularly, a fast pressure swing adsorption system
with low void volume, improved flow distribution, and
enhanced process performance.

Background of the Invention

Adsorption processes have been widely used for the
separation and purification of gases. In recent years,
pressure swing adsorption (PSA) systems including
vacuum PSA (VPSA) have been developed for enhanced gas
separation operations, particularly for the commercial
production of oxygen and/or nitrogen from air. The PSA
process consists of basic steps such as adsorption-
desorption. Air or another gas mixture is fed into the
system, which includes one or more vessels, each with
an adsorbent bed, to an upper adsorption pressure. The
adsorbent beds (a.k.a. adsorbers) selectively adsorb
the more readily adsorbable component(s) of the air or
gas mixture. The less readily adsorbable component(s)
passes through the adsorber. The vessel is then
depressurized to a lower desorption pressure for the
desorption of the more readily adsorbable component(s)
from the adsorber(s), which is then repressurized to
the upper adsorption pressure as cyclic operation is
continued.

In order to improve performance, conventional PSA
systems typically use two or more vessels in parallel
with directional valves to connect the vessels in

alternating sequence to the compressor or vacuum pump.
Further, to fully utilize the adsorbent material
employed, PSA systems require uniform flow of gas
across the adsorbent vessel(s) throughout the PSA
5   processing cycle. In addition, void volume and
pressure drops in the PSA vessel entrance and exit
regions (i.e., the inlets and outlets and their
associated headers) have adverse effects on the process
performance of a PSA system and must be minimized in
10   practical commercial operations. Ruthven, et al.
disclose a method for estimating the magnitude of
effects by void volume via an equilibrium model. More
specifically, they examined the effects of void volume
in a simple four-step cycle with a linear isotherm, and
15   showed that large void volume could significantly
reduce recovery. Unfortunately, the study applies to
an idealized situation without consideration of mass
transfer resistance, heat effect and isotherm non-
linearity. In addition, only production end void
20   volume and a simple cycle are investigated.
US Patent 5,968,233 to Rouge, et al. discloses a
similar conclusion of void effects for a more realistic
air separation cycle. However, the patent focuses only
on production end void volume. More importantly, the
25   patent looks for an optimum void volume for oxygen
cost, rather than a minimum void volume.

         The effect of void volume varies depending on the
location of the void (relative to the adsorbent) and on
which step of the cycle the void is considered. For
30   example, the light product gas in the production end
void space serves, to some extent, as a purge gas
during a countercurrent regeneration step; however,

3

this purge is less effective than a controlled purge at low pressure. Also, the gas and compression work in both the production and feed end voids can be partially recovered during an equalization step. However, the

5   losses of compressed gas and work during regeneration can be significant. In general, lower void volume ratio results in improved process performance (i.e., improved recovery, power consumption, etc. without considering flow distribution requirements and

10 increasing fabrication costs).

Conventional methods for reducing PSA void spaces and improving process performance typically falls into the following classes: (a) vessel system with improved headers, (b) single-vessel system, and (c) piston-

15 driven PSA system.

Vessel system design is a classic approach, focusing only on the vessel or bed itself. Vessels are designed to improve flow distribution and minimize void spaces within the vessel ends (or headers) between the

20 gas inlet (feed end) or outlet (production end) and the adsorbent. US Patent 5,759,242 to Smolarek, et al., which describes a radial adsorber, and US Patent 5,538,544 to Nowobilski, et al., which describes a conventional vertical adsorber, are two recent examples

25 of this approach. However, the vessel design approach has its limits for reducing void space. With a given flow distributor, it can only decrease header space to a level where flow maldistribution and pressure drop are acceptable for the process. In addition, void

30 spaces in distribution pipes are not addressed by this approach.

4

The single-vessel pressure swing adsorption system disclosed in US Patent 4,194,892 to Jones, et al., is a rapid pressure swing adsorption (RPSA) system, which utilizes a single vessel filled with small adsorbent

5 particles as well as very short cycle times (as short as a few seconds). It is worth noting that US Patent 4,194,892's primary purpose is not to reduce void space, but instead to reduce cycle time and adsorbent inventory and to eliminate multiple vessels. However,

10 the use of a single bed can theoretically eliminate the distribution pipes (and then their voids) connecting a compressor or vacuum pump to different vessels in a multiple vessel PSA. The disadvantages of the single bed PSA are: (1) void space in the vessel header is

15 not addressed and (2) product recovery is limited (in comparison to multiple vessel PSA) without an additional storage tank and recycle component.

US Patent 4,354,859 to Keller, et al. teaches a pressure swing parametric pumping process. This

20 system, called a piston-driven PSA system, uses two synchronized pistons to pressurize and depressurize a single adsorber that is fed near the center of the adsorbent bed. Farooq, et al., Separation and Purification Technology 13 (1998) 181, applied this

25 approach to a parallel passage adsorber for nitrogen and carbon dioxide separation. Suzuki, et al., Adsorption 2 (1996) 111 also utilized this approach in a single piston system for oxygen enrichment from air. This approach can theoretically eliminate header void

30 spaces associated with conventional PSA systems. Moreover, there is no need for valves because flows can be controlled by the piston movement. However, the

piston-driven PSA system suffers from scale-up
difficulties. For instance, a very large piston is
normally required for a large production unit. A
piston of this size would be difficult to manufacture.
5   Also, like the single bed PSA, the piston driven PSA
suffers from low recovery in comparison to a
conventional multiple vessel PSA.

Illustratively, European Patent Application
0,879,630 A2 to Garrett and La Cava extends the piston-
10   driven PSA concept to a system with two sets of pistons
or diaphragms. A first set of pistons or diaphragms is
located at the top and bottom of the bed to influence
fluid flow, as well as a second set of pistons or
diaphragms at the side walls of the adsorber. The
15   second set fractionally increases and decreases bed
pressure prior to the adsorption and desorption steps,
respectively. The Garrett and La Cava patent
application teaches that using two sets is more
efficient than only using one set. Nonetheless, as
20   acknowledged by Garrett and LaCava, its recovery is
low. In addition, the second set of pistons or
diaphragms complicates the process.

The present invention addresses the limitations of
conventional vessel designs, single vessel PSA, and
25   piston-driven PSA systems. The present invention not
only minimizes the header void spaces within each
vessel, but also improves distribution pipe void spaces
between the compressor/vacuum pump and each vessel.
Moreover, the present invention can use multiple
30   compressors and/or vacuum pumps to better distribute
flow and further reduce the void spaces.

Summary of the Invention

The present invention provides a novel PSA system
and process with low void volume (also called "void
spaces") and improved flow distribution that is

5   adequate for fast cycle processes. This system can
also be adapted for use in combined piston-driven and
conventional multi-bed PSA systems as well as in bed-
to-bed interactions.

In one embodiment of the present invention, a low

10   pressure swing adsorption system is taught wherein flow
movement and pressure pulse are influenced from the
same pressure source. The pressure source may be a
high pressure source or a low pressure sink. The
system includes at least one vessel containing an

15   adsorbent bed. An inlet (feed end) is coupled to the
vessel by way of an inlet header and an outlet
(production end) is coupled to the vessel by way of an
outlet header. The inlet header and the outlet header
of each vessel have a combined volume of less than

20   approximately 20% of the volume of the adsorbent bed.
Preferably, this volume is limited to less than 10% and
most preferably to less than 5%. Each inlet is coupled
to a high pressure source or a low pressure sink. This
configuration is depicted in Figure 2a and 2b,

25   discussed in detail below. It is notable that void
volumes of less than about 20% of the adsorbent bed can
be achieved in nearly all bed configurations except
radial bed configurations. One skilled in the art
would acknowledge that void volumes this low are not

30   readily realized in radial bed configurations. For
radial beds, the present invention can achieve void
volumes of less than 50%.

In a second embodiment, depicted in Figure 2c, each vessel has an adsorbent bed with an inlet header and an outlet header. Each vessel has at least one outlet and more than one inlet. Mounted proximate to each inlet is a high pressure source or a low pressure sink. As in the first embodiment, the total volume of the inlet and outlet headers of each vessel is limited to less than approximately 20% of the volume of the adsorbent bed of that vessel. More preferably, this volume is less than 10% and most preferably less than 5%.

In a third and most preferred embodiment, as depicted in Figure 2d, each vessel has an adsorbent bed, an outlet header and an inlet header. Further, each vessel has at least one outlet and more than one inlet. Each inlet is coupled to a valve mounted proximate to said vessel. All valves share a common high pressure source and/or low pressure sink. Again, the total volume of the inlet and outlet headers of each vessel is limited to less than approximately 20% of the volume of the adsorbent bed of that vessel. More preferably, this volume is less than 10% and most preferably less than 5%. To increase the efficiency of this embodiment distribution pipes connecting in the inlet valves to the high pressure source or low pressure sink should be maintained at high or low pressures, respectively. The total volume of the distribution pipes may also be limited to less than approximately 10% of the total volume of the adsorbent bed(s).

All void volume situated between the inlet and pressure source may be collectively referred to as feed

end intermediary volume. This feed end intermediary
volume is depicted in the figures as S1, S1', V5, V5'
and V4. While silencers are depicted in the figures,
the void source may be any system components and their
5 associated volumes situated between the inlet and the
pressure source and subjected to pressure changes.
Thus, the term "intermediary volume" may include pipes,
silencers, tanks, or any other void source that happens
to be located in this area. In accordance with the
10 present invention, this intermediary void volume may be
limited to less than 15-20% of the total volume of the
adsorbent bed(s).
The adsorbent bed(s) may be configured radially,
vertically or, most preferably, configured as a flat
15 header bed. In addition, the high pressure source may
be of any type known to those skilled in the art;
however, a compressor is preferable, such as a
conventional Roots type compressor or a linear
compressor (i.e., a piston compressor driven by a
20 linear motor). The present invention may be employed
wherein the piston compressor is comprised of more than
one piston.

A low pressure sink may be used in conjunction
with, or as an alternative to, the high pressure source
25 described above. Any low pressure sink may be employed
in the system of the present invention; however, a
vacuum pump is preferred.

One object of the present invention is to reduce
the void volume in both the feed end (inlet) and the
30 production end (outlet) for fast PSA processes with
reduced cycle time. A further object of the present
invention is to provide a system with improved product

gas production and improved adsorbent utilization.
Another object of the present invention is to provide a
system with reduced intermediary volume relative to the
adsorbent bed(s) volume. Yet a further object is to
present an efficient low void adsorption system that
can be readily adaptable to single or multiple bed
configurations as well as various bed configurations.
Other features and advantages of the present invention
will be apparent from the following detailed
description and when read in conjunction with the
accompanying drawings.

Brief Description of the Drawings

Figure 1 is a schematic depicting a conventional
PSA.

Figure 2a is a schematic depicting a single bed
system with low void space. This schematic shows a
single bed with a high pressure source and a low
pressure sink coupled to said bed.

Figure 2b is a schematic depicting a two bed
system with low void space.

Figure 2c is a schematic depicting a flat header
bed with closely mounted compressors and/or vacuum
pumps.

Figure 2d is a schematic depicting a flat header
bed in which inlet valves are mounted proximate to the
inlet header. These inlet valves share a common high
pressure source or low pressure sink.

Figure 3 is a schematic depicting a radial bed.
Figure 3a is a top view of this radial bed while Figure
3b is a side view of the radial bed.

Figure 4 is a schematic depicting the top view of a segmented vertical bed, different sections are separated by dividers which undergo different PSA process steps such as adsorption, desorption, and

5   equalization, etc.

Figure 5 is a schematic depicting a vertical plate bed.

Figure 6 is a schematic depicting a representative process cycle.

10   Figure 7 is a graph depicting the void influence on recovery and power. Case A is the prior art (as shown in Figure 1) but with a fast cycle time (approximately 2 seconds), low recovery and high power. Case B is the present invention with a reduced

15   distribution pipe void volume as shown in Figure 2b. Case C is the present invention with a flat header as shown in Figure 2d. The two-bed system has a high pressure equal to 1.5 bars and a low pressure equal to 0.3 bars, an O_2 purity equal to 90% and a cycle time

20   equal to approximately 1 to 2 seconds.

Detailed Description of the Invention

The present invention provides a pressure swing adsorption (PSA) system with a low void volume and

25   enhanced process performance in which the void space in the inlet and outlet headers, the feed and vacuum distribution pipes and silencers is limited. In the disclosed embodiments, pressure sources, such as high pressure sources and/or low pressure sinks, are mounted

30   proximate to, or nearly proximate to, the vessels. The present invention may suitably employ multiple inlets

and/or multiple outlets to improve flow distribution and further decrease void volume.

Throughout this document, the terms "inlet" and "feed end" are used interchangeably and are intended to

5   carry essentially the same meaning. Likewise, the terms "outlet" and "production end" are used interchangeably and are intended to carry essentially the same meaning.

Besides enhanced adsorption, the present invention

10 results in a system with fast cycle times as compared with conventional PSA system performance. Using short cycles times may reduce adsorbent inventory, make PSA systems more compact, and increase productivity. This feature is especially important for medical

15 applications such as oxygen concentrators. Therefore, decreasing cycle time has become a central point in PSA development. The present invention reduces the conventional 30 second cycle time by an order of magnitude.

20 The present invention has at least four advantages in low void volume, flow distribution and process performance as compared with the systems taught in the prior art. First, those skilled in the art understand that distribution pipes (also called feed distribution

25 pipes and vacuum distribution pipes) connecting high pressure sources and/or low pressure sinks to the vessel contribute to total void space, thereby reducing the efficiency of the system. The present invention discloses that these high pressure sources and/or low

30 pressure sinks can be mounted proximate to, or nearly proximate to, the vessels, thereby eliminating the need for these feed and vacuum distribution pipes and their

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associated volume. Likewise, silencers contribute to total void space and may be reduced or eliminated as disclosed in the present invention to reduce void space and improve system efficiency. On this basis,

5   significant void volume reduction and process performance improvement are achieved in comparison with a conventional multi-bed PSA.

Second, more than one high pressure source and/or low pressure sink may be mounted proximate to, a nearly

10   proximate to, each vessel, by suitably employing multiple inlets and/or outlets. These inlets and outlets improve flow distribution within the adsorbent bed headers and reduce header void space. For example, the ratio of the volume of the void space to the volume

15   of the adsorbent bed is minimized. The resultant system has a reduced total void space as compared with the PSA systems taught in the prior art.

Third, the configuration taught herein removes the scale-up difficulties associated with Suzuki, et al.'s

20   piston-driven system. Under the present invention, a series of smaller pistons may be suitably employed to replace one large piston, by using the multiple feeds.

Fourth, multi-beds and bed-to-bed interactions may be suitably employed to improve overall performance.

25   Figure 1 represents a PSA system equivalent to that taught in the prior art. These systems tend to have large distribution pipe volumes, large header volumes and large cycle times (approximately 30 seconds). A configuration with two vertical vessels 10

30   and 10' each with an adsorbent bed 11 and 11' with volumes V1 and V1', respectively, is chosen for illustration purposes only and is intended to be a non-

limiting representative example. The configuration of Figure 1 also includes inlets 13 and 13' connected to the adsorbent bed by way of inlet headers 12 and 12', outlets 15 and 15' connected to the adsorbent beds by

5   way of outlet headers 14 and 14', a low pressure sink 17, and a high pressure source 19. Inlet headers 12 and 12' have volumes $V2$ and $V2'$, respectively. Outlet headers 14 and 14' have volumes $V3$ and $V3'$. A conventional system typically consists of the following

10 void spaces:

1)   Headers – Inlet headers 12 and 12' and outlet headers 14 and 14' represent void space. In the case of a conventional vertical adsorbent bed configuration, the inlet and outlet headers comprise a

15 void space equivalent to approximately 16 to 20% of the volume of the adsorbent bed. In the case of radial beds, the inlet and outlet headers have a void space equivalent to approximately 20 to 60% of the volume of the adsorbent bed.

20 2)   Distribution Pipes – Distribution pipes D1, D2, D3 and D4 connect the high pressure source to the adsorbent beds (feed distribution pipes) and connect the low pressure sink to the adsorbent beds (vacuum distribution pipes), collectively referred to as "feed

25 end pipe volume." Total volume of the feed end (inlet) pipes equals $V4$. Distribution pipe D7 connects the production tanks to the adsorbent bed. The volume of the production end (outlet) distribution pipes D7 is referred to collectively as $V7$. These pipes represent

30 void space of approximately equal to 5 to 10% of the volume of the adsorbent bed.

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3) Silencer – Silencer S1 with volume V5, such as a tank positioned between the high pressure source or low pressure sink and the adsorbent bed, also represents void space. Further, such tanks S2 with volume V8 may be situated on the production end. Typically, these silencers have a void space equivalent to approximately 5 to 10% of the volume of the adsorbent bed.

The total void space volume is the sum of these three void spaces. There is a large amount of irreversible work present in these void spaces due to pressure changes in the PSA process, representing a significant loss of power and process performance. This power loss increases with an increase in the ratio of high to low pressure.

Further, product gases remained trapped in these voids upon saturation of the adsorbent bed and are lost during regeneration of the adsorbent bed. Therefore, larger void spaces represent lost product.

In accordance with the present invention, systems within the following void space parameters may be developed by mounting high pressure sources and/or low pressure sinks proximate to, or nearly proximate to, the adsorbent bed typically in-line with fluid flow through the adsorbent bed so that pressure pulse and flow movement are influenced from the same pressure source.

$$20\% \geq \frac{\text{volume of the inlet headers } (V2+V2') + \text{volume of the outlet headers } (V3+V3')}{\text{volume of the adsorbent beds } (V1+V1')}$$

$$10\% \geq \text{volume of the distribution pipes } (V4 + V7)$$

volume of the adsorbent beds (V1+V1')

$$10\% \geq \frac{\text{volume of the silencers (V5 + V5' + V8)}}{\text{volume of the adsorbent beds (V1+V1')}}$$

The present invention also discloses that the total void space of silencers, tanks, pipes and other various sources of void space located between the inlet and the pressure sources may likewise be limited to about 20% of the adsorbent volume.

Note that in the case of radial bed configurations, header void space tends to be generally larger. Therefore, for radial beds, equation (1) is modified to:

$$50\% \geq \frac{\text{volume of the inlet headers (V2+V2') + volume of the outlet headers (V3+V3')}}{\text{volume of the adsorbent beds (V1+V1')}}$$

Mounting the high pressure source and low pressure sink proximate to, or nearly proximate to, the vessel allows for less distribution pipe volumes, thereby reducing total void space.

In conventional systems, bed fluidization, pressure drop, and compressor capacity typically limit flow rate. One conventional method to increase productivity includes reducing the bed length and increasing the cross-sectional area of the bed. However, shorter bed lengths and larger bed diameters often result in a higher ratio of the void volume relative to the adsorbent bed volume. For instance, the total void volume ratio of a conventional axial-bed PSA system is about 30%, and the process cycle time is about 30 seconds. Reduction of the cycle time by 50%

(i.e., from 30 seconds to 15 seconds) by cutting the
bed length by 50%, approximately doubles the total void
volume ratio (i.e., from 30% to 60%) since the inlet
(feed end) and outlet (production end) void volumes
5   remain the same. The increased void volume ratio
dramatically decreases the process performance.
Therefore, the void volume reduction is a key for fast
PSA system developments.

     Figure 2a illustrates one non-limiting embodiment
10   of the present invention using a single vertical bed.
A vessel 20 has an adsorbent bed 21 (with volume V1)
with an inlet 23 coupled thereto by way of an inlet
header 22 (with volume V2). The inlet 23 draws feed
gases or feed gas mixtures to the adsorbent bed 21 for
15   purification or other treatment. Likewise, an outlet
25 is coupled to said adsorbent bed 21 by way of an
outlet header 24 (with volume V3). The outlet 25
provides processed gases also called product gases.
Connected to each vessel via the inlet header is a high
20   pressure source 27 or low pressure sink 29. These
sources 27 or sinks 29 may be coupled to the vessel 20
in a variety of ways; however, Figure 2a depicts valves
30 and 31 coupling the sources 27 or sinks 29 to the
vessel 20. Although Figure 2a depicts both a high
25   pressure source 27 and a low pressure sink 29, these
sources and sinks may be used in the alternative or in
concert.

     The vessel is typically filled with an adsorbent
suitable to the product desired, such as a nitrogen
30   selective adsorbent that produces an oxygen product.
The high pressure source may be any type of compressor,
such as a conventional Roots type or linear compressor.

The linear compressor is a piston compressor driven by
a linear motor. These types of linear compressors have
a higher efficiency and improved performance. In
addition, it is easy to modulate capacity or flow with
5   piston compressors; such a feature is very useful in
medical concentrators. Furthermore, linear compressors
may be modified to operate as a vacuum pump. The low
pressure sink may be of any configuration, suitable to
the system, however, a vacuum pump is preferred. The
10   high pressure source and low pressure sink may be used
in the alternative or in concert.

    Figure 2b depicts a two-bed embodiment of the
present invention. This embodiment contains two
vessels 20 and 20' each with an adsorbent bed 21 and
15   21' (with volumes V1 and V1', respectively), an inlet
header 22 and 22' (with volumes V2 and V2',
respectively), an inlet 23 and 23', an outlet header 24
and 24' (with volumes V3 and V3', respectively), an
outlet 25 and 25', and either a high pressure source 27
20   and 27' or a low pressure sink 29 and 29'. The high
pressure source and low pressure sink may be used in
the alternative or in concert. Note that pipe D5 (with
volume V4) and valve 32 are used for inlet-inlet
equalization between the two vessels, if necessary.
25   Distribution pipe D7 on the production (outlet) end of
the system has volume V7. Any combination or mixture
of high pressure source(s) or low pressure sink(s) are
acceptable. Further, although two beds/vessels are
shown, any number of beds/vessels may be suitably
30   employed.

    Also depicted in Figure 2b are silencers S1, S1',
and S2 having volumes V5, V5', and V8, respectively.

These silencers are intended to represent all void
sources, such as silencers, tanks, pipes, etc.,
situated between the inlet and the pressure source.
Those skilled in the art would recognize that various

5   void sources, not solely silencers, may be situated in
the system. These silencer volumes V5, V5,', and V8,
distribution pipe volumes V4 and V7, and other void
volume sources V6 (not shown) are collectively referred
to as intermediary volumes V10 (not shown) and may be

10   limited in accordance with the present invention.
These volumes may be limited to less than approximately
15-20% of the total adsorbent bed volume.

Figure 2c shows yet another non-limiting
embodiment of the present invention using a flat header

15   bed with closely mounted compressors and/or vacuum
pumps. In this embodiment the high pressure source(s)
27 and low pressure sink(s) 29 are mounted immediately
proximate to the inlet header 22 of the adsorbent bed
21.   In such a configuration, at least one outlet 25 is

20   coupled to the outlet header 24 of vessel 20.

Since the separation work in a PSA process is only
done in the adsorbent, the rest of the void (i.e., non-
adsorbent) volumes, such as distribution pipes and
absorber headers, must be minimized for improved

25   process performance. In conventional bed headers, a
single inlet or outlet is normally used. A certain
volume is needed for distributing gas flows from the
inlet or outlet uniformly to the adsorbent for better
use of the adsorbent and process performance. Multiple

30   inlets or outlets can provide a better flow
distribution and require less header volume. The
number of inlets or outlets depends on a number of

factors, for example, product flow, diameter/size of
the bed, high pressure source/low pressure sink
capacity, etc. If enough inlets or outlets are
provided, the flow distribution header volume could be

5   virtually eliminated and a quasi-flat header could be
obtained as illustrated in Figure 2c. Compared with a
conventional header, the flat header design can save up
to 15-20% (and in some instances 5-10%) of the volume
of a vertical bed configuration of a 150 TDP oxygen

10   plant, and approximately 20-60% (and in some instances
10-20%) for a radial bed.

Figure 2d shows a further non-limiting embodiment
of the present invention using two flat header
adsorbent beds 21 and 21' (with volumes V1 and V1',

15   respectively) are connected to to a common high
pressure source 27 (i.e., compressor) and/or low
pressure sink 29 (for example, a vacuum pump) by way of
distributed valves. Valves 36, 36', 37 and 37'
represent inlets and may be mounted immediately

20   proximate to the inlet headers 22 and 22' (with volumes
V2 and V2', respectively). Likewise, valves 33 and 33'
represent outlets and may be coupled proximate to the
outlet headers 24 and 24' (with volumes V3 and V3',
respectively). Valves 36 and 36' are connected to

25   common distribution pipes D6 and share a low pressure
sink 29. Valves 37 and 37' are connected to common
distribution pipes and share a high pressure source 27.
As in the embodiment of Figure 2d, ideally the
distribution pipes D5 and D6 should be maintained at

30   either high pressure or low pressure depending on
whether they are connecting the high pressure source or
low pressure sink, respectively, to the vessel. The

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valves can provide the multiple flow inlets and outlets

required by a flat header, thereby reducing the header

void volume. Three-way unloading valves (38 and 39)

and distributed valves can be suitably employed to

5   close the distribution pipes to pressure changes, for

example during an idle step, and maintain either high

or low pressure. Therefore, the distribution pipe

volume (V4 and V7) does not contribute, or contributes

little to, power loss and the total void volume. In

10   this embodiment, one high pressure source and/or one

low pressure sink may be sufficient for the entire

system. Alternatively, multiple high pressure sources

and/or low pressure sink may be employed.

Figure 2d also depicts silencers S1, S1', and S2

15   with volumes V5, V5', and V8, respectively. These

silencers contribute to intermediary volume V10 (not

shown) along with distribution pipe volumes V4 and V7,

and other miscellaneous volumes V6 (not shown). As

discussed above, V6 includes all volumes and not solely

20   silencers, that may be situated between the inlet and

the pressure source(s) or on the production (oulet)

end. In accordance with the present invention, these

void sources may be limited to less than 20-15% of the

total volume of the total adsorbent bed volume.

25   Figures 3a and 3b depict a radial bed configuration

also suitable in the present invention. Figure 3a

depicts a top view of the bed and Figure 3b depicts a

side view. Figure 3b shows a radial configuration

where the high pressure source and/or low pressure

30   sink, and valves are distributed along the

circumference of the bed. In addition, the bed may be

segmented (or divided, structured) as shown in Figure

4. Figure 4 depicts a segmented vertical adsorber
configuration, wherein each segment functions as an
individual adsorbent bed. Moreover, the beds may be
very shallow and arranged in a parallel configuration
5 where two adjacent beds (or compartments) share a
common feed, evacuation and product withdrawal. The
system can also be a vertical bed as shown in Figure 5.

Any process cycle with basic adsorption and
desorption steps may suitably employ the configurations
10 disclosed herein to improve void volume and efficiency.
A representative PSA cycle using two adsorbers is
selected for illustrative purposes, as shown in Figure
6. The cycle consists of the following steps:

Simultaneous feed and product pressurization
15 (FP/PP)

Adsorption and purge (AD/PG)

Both end equalization (EQ)

Evacuation (EV)

Evacuation and purge (EV)

20 Equalization (EQ/FP)

Three overlapping steps are used in this cycle:
simultaneous feed and product (FP/PP), dual end
equalization (EQ), and simultaneous dual end
equalization and feed. These overlapping steps create
25 a continuous feed thereby reducing cycle time.
During step 1 (FP/PP) shown in the process cycle of
Figure 6 and as shown in the two-bed system of Figure
2b, air containing oxygen and nitrogen is compressed
and sent to bed 21 through valve 30. At the same time,
30 high pressure oxygen product is concurrently introduced
to bed 21 through valves 33, 34, and 35. When the
pressure in the bed reaches adsorption level, step 2

(AD/PG) starts. One portion of oxygen starts flowing
from bed 21 through valves 33, 34 and 35 and collected
as product. During all these times, bed 21' undergoes
two evacuation steps (steps 4 and 5, EV) through valve

5   31'. When oxygen concentration leaving bed 21 is no
longer acceptable, valve 34 is closed. Valve 31' is
also closed while valves 30' and 32 are open and step 3
(EQ) starts for bed 21, while bed 21' undergoes step 6
(EQ/FP). When the pressures between the two beds are

10   approximately equal, equalization steps (EQ and EQ/FP)
are stopped and the second half of the cycle takes
place wherein the steps are repeated. For example, bed
21' processes the air while bed 21 recharges, during
which time valve 33' performs the same functions

15   earlier performed by valve 33, valve 30' performs the
same functions earlier performed by valve 30, and valve
31' performs the same functions earlier performed by
valve 31.

        The improvement in process performance as a result

20   of the reduced void volume is illustrated in Figure 7.
A simple air separation process with different void
volumes is simulated for this purpose. A highly
exchanged LiX zeolite (SiO_2/Al_2O_3 ratio of between about
2.0 to 2.5) is chosen for adsorbent. The adsorbent

25   particle size is kept constant for this comparison.
The operating pressure ratio (adsorption/desorption) is
about 5. The process performance is based on oxygen
recovery wherein oxygen product purity is maintained at
about 90%. The oxygen recovery is defined by the ratio

30   of the oxygen in the product over the oxygen in the
feed.

23

Figure 7 illustrates the influence of the void
volume on the performance of fast cycle processes.
Given, for example, a conventional axial-bed PSA system
(such as that shown in Figure 1) with a cycle time of
5   about 10 seconds and a void volume of about 14%. In
order to reduce cycle time to 2 seconds, the bed length
must be reduced to one-fifth of its original size.
Such a reduction in bed length corresponds to a void
volume increase of about 70%. With such a large void
10   volume, oxygen recovery will decrease to about 20%, as
indicated by case A of Figure 7. Therefore, a
conventional bed configuration cannot achieve fast
cycle times without greatly compromising product
recovery.

15   By contrast, using the configuration disclosed in
the present invention, the distribution pipes can be
avoided as in Figure 2b, resulting in a reduction of
the void volume to about 50%. Such a reduction
increases recovery to about 25%, as indicated by case B
20   in Figure 7. Furthermore, in the present invention, if
two flat headers are used as shown in Figures 2c and
2d, the void volume can be reduced to a few percent of
the adsorbent bed, resulting in a recovery of more than
50%, as indicated by case C in Figure 4. Thus, the
25   present invention reduces cycle time while
significantly improving recovery.

Similarly, the void volume has a very important
effect on power consumption for fast cycle process
because large amounts of power are generally lost in
30   the voids. Simulations indicate that as compared with
70% void case A, the present invention can reduce power

by 16% in case B by eliminating the distribution void,
and up to 50% in case C by using flat headers.
It should be understood that the foregoing description
is only illustrative of the invention. Various

5   alternative and modifications can be devised by those
skilled in the art without departing from the
invention. Accordingly, the present invention is
intended to embrace all such alternatives,
modifications and variances which fall within the scope

10   of the appended claims. More particularly, the system,
although presented here with a one or two bed
embodiment, can be practiced with more beds. Further,
the invention is not restricted to a single adsorbent.
Multiple adsorbents can be employed. Also, adsorbents

15   could be layered or mixed within a bed. The adsorbents
should not be limited to nitrogen selective adsorbents
mentioned above, other adsorbents can be employed as
well. Although the process of the present invention is
preferably operated near atmospheric pressures and

20   ambient temperatures, it can be applied to a full range
of process conditions, e.g., pressures, temperature,
and flow rate, etc.

Further, bed-to-bed equalizations or interactions
are not limited to what is described in the present

25   invention. Other arrangements can be used. When the
bed is a segmented one, equalizations can be between
segments. Furthermore, the present invention is not
limited to the embodiments described herein, various
other configurations may be suitable employed. In

30   addition, the linear compressor is not limited to a
piston compressor driven by a linear motor mentioned
above. It can be a compressor driven by any

electrical, magnetic or audio forces. While the
examples are presented for an air separation system,
the present invention is not intended to be limited to
binary air separation. The principles of the present
5   invention can be applied to any separation,
purification and recovery system.